Atmospheric Electricity over the Ocean.

By G. C. SIMPSON, D.Sc., and C. S. WRIGHT, B.A.

(Communicated by Arthur Schuster, F.R.S. Received January 20,—Read January 26, 1911.)

Although the different phenomena of atmospheric electricity have been thoroughly investigated over land, very little work has yet been done over the ocean, and on the few occasions on which experiments have been made, the observations have been too few to give conclusive results. It was thought that the long voyage from England to New Zealand of Captain Scott's Antarctic ship "Terra Nova" would furnish an excellent opportunity for continuing these investigations. The plan of the work to be undertaken was:—

(1) To investigate the electrical potential-gradient existing over the ocean.

(2) To investigate the quantity of the radioactive products in the air.

(3) To measure the number of free ions over the ocean.

(4) To investigate the ionisation of the air in a closed vessel, with the object of determining the presence or absence of a penetrating radiation over the sea.

One of the chief difficulties which has hindered the work of previous investigators has been the want of a suitable electroscope for use on the sea, the only instrument which had been available being the leaf electroscope in one or other of its numerous forms. It is obvious that this instrument could not be used with accuracy on a ship rolling to an appreciable degree. There has, however, recently been put upon the market an electroscope designed by Prof. P. T. Wulf, of Holland,* which does not depend upon gravity for equilibrating the electrical force, but upon the tension of a small bow of quartz fibre. This instrument, which is excellently made by Günther and Tegetmeyer, of Brunswick, has been used in all our work, and has proved itself capable of giving a high degree of accuracy, even when the ship was rolling as much as 25° from the vertical.

(1) *Potential-gradient.*

As far as we have been able to discover, the only measurements of the potential-gradient made over the sea are those of Exner, who observed during a voyage from Aden to Bombay in 1888.† Exner's results are valuable, but they do not settle the three important questions:—

(1) Is the potential-gradient over the centres of the great oceans of the same sign as over the land?

---

* Wulf, 'Phys. Zeit.,' 1907, vol. 8, pp. 246, 527.

† Exner, 'Wien. Ber.,' 1899, vol. 108, p. 371.

(2) Is it of approximately the same magnitude?

(3) Is the daily range over the ocean similar to that over the land?

It is towards the solution of these problems that our work has been directed.

Our methods were in the main similar to those used on land, but instead of a water-dropper or a flame, we used a radioactive substance for bringing the collector-rod to the potential of the air at its end. Objections have been raised against the use of radium itself for this purpose, as the β- and γ-rays ionise the air to a considerable distance from the radium, so that not only are the conditions under investigation affected by the presence of the radium, but it is impossible to fix with sufficient accuracy the point in the atmosphere to which the potential measured by the instrument refers.

On talking over with Profs. Elster and Geitel the question of the best collector to be used in the Antarctic, they suggested ionium, because this element does not appreciably decay with time and gives out only α-rays, the ionising power of which is limited to a few millimetres. Prof. Giesel generously placed a comparatively large amount of this rare substance at our disposal, and Profs. Elster and Geitel very kindly experimented to determine the best method of applying it to the ends of our collector rods. The collector as used consisted of a short copper rod coated with ionium, attached to a thin wooden rod 110 cm. long, cemented by means of sulphur at its lower end into a brass tube. The latter was then fastened by means of grips to a retort stand, the sulphur cement efficiently insulating the rod from the earth-connected stand. A wire connected the collector to a Wulf electroscope.

The Sign of the Potential-gradient.—During the whole voyage, observations were made every few days to determine the sign of the potential-gradient, and it was found to be, without exception, positive on fine days.

The Daily Range of the Potential-gradient.—In order to obtain the form of the curve representing the daily range of the potential-gradient, it is only necessary to fix the collector in some position, the surroundings of which do not change, and then to take observations during periods of fine weather. This, however, was found to be impossible on the "Terra Nova," for there was absolutely no spot on the ship which was not dominated by yards, sails, and ropes, the positions of which were constantly being changed. The only thing to be done was to take every opportunity of a spell of settled weather to make observations, when there was a probability of the sails remaining in one position for several hours. On each occasion the most suitable position on the ship in which to set up the collector had to be chosen; in some cases this was in the bow of the ship, and in others at the stern. Thus no two series of measurements could be joined up, for even when the same position was used a second time, the yards were probably trimmed differently at each observation. As a set of observations was of little use unless it extended over a period of approximately 24 hours, during which the sails and yards were not moved, a large amount of work was wasted, for observations were started on several occasions which had to be abandoned owing to a change in the position of the sails, or to a change in the weather conditions which disturbed the normal potential-gradient.

The method of making the observations was as follows :—The position for the collector being chosen and the apparatus set up, the electroscope was read at the end of each minute. It was deemed necessary to make these frequent readings in order to get a mean which would be independent of the rapid changes of the potential-gradient, and would cut out errors due to the changing position of the collector relative to the sea surface caused by the roll of the ship.

Table I gives the result of the few series which were sufficiently extended to be useful for our purpose. With the exception of Series IV, V, and VI, the numbers are on an arbitrary scale, and, as stated above, those of one series are not directly comparable with those of another. The mean value for an hour is the mean of the 60 readings extending from half an hour before to half an hour after the hour.

The numbers are plotted in the respective curves of fig. 1.

Series I.—The observations commenced at 17 h. 30 m. (mid-day written 12 h.) on July 14, when the ship was in lat. 2° N. and long. 21° 36′ W., and extended to 10 h. 30 m. on July 16, when the position of the ship was 0° 58′ S. and 21° 17′ W. Thus the whole series was obtained within nearly 2° of the Equator. The weather was fine during the whole period, with cloud amounts varying from 0 to 6. The observations had to be stopped owing to the setting of the sails.

Series II extended from 15 h. 30 m. on July 21 to 13 h. 30 m. on July 22, the position of the ship being 11° 15′ S. and 26° 2′ W. at the commencement, and 12° 34′ S., 27° 5′ W. at the end. The weather was not at all satisfactory during this series of observations. When the observations commenced the sky was clear to within 20° of the horizon, but in the east there was a bank of fairly heavy stratus clouds. This bank steadily rose and became thicker, and at 18 h. 15 m. clouds from it had reached the zenith. At 19 h. 30 m. the sky was quite overcast with cumulo-stratus clouds, and at 20 h. 22 m. a few drops of rain fell. From this time until 22 h. 36 m. there were rain squalls on the horizon, and every now and then a few drops of rain would fall on the ship. The clouds commenced to clear at 22 h. 40 m.,

Table I.

	Series I.			Series II.		Series III.	Series IV.			Series V.		Series VI.
	Arbitrary scale.			Arbitrary scale.		Arbitrary scale.	Volts/metre.			Volts/metre.		Volts/metre.
	July 14.	July 15.	July 16.	July 21.	July 22.	July 25.	Aug. 3.	Aug. 4.	Aug. 5.	Sept. 24.	Sept. 25.	Sept. 26.
Midnight		304	274		183			116	124		130	
1		305	273		206			108	128		138	
2		312	300		201			96	108		125	
3		298	342		202			100	100		136	
4		280	392		211			108			107	
5		281	395		222			108			109	
6		289*	446*		224*			100*			—*	
7		300	397		217			96			97	
8		273	367		216			96			101	
9		225	383		213	243		76			99	
10		232	337		215	236		96				79
11		215			218	217		104				77
Midday		249			216	209	84	96				81
13		251			203	218	96	84				80
14		—				218	104	92				76
15		305				208	100	92		100		85
16		332		247		238	108	88		93		86
17		387		263		260	116	124		88		
18	397†	382†		253†			120†	156†		94†		
19	400	381		256			124	148		91		
20	378	361		231			136	164		103		
21	389	335		245			140	144		106		
22	328	314		232			136	124		110		
23	312	286		208			136	108		123		

* Sun rose during this hour.

† Sun set during this hour.

and by 1 h. they had practically all disappeared; after this the cloud amount remained below 4, until the observations were stopped.

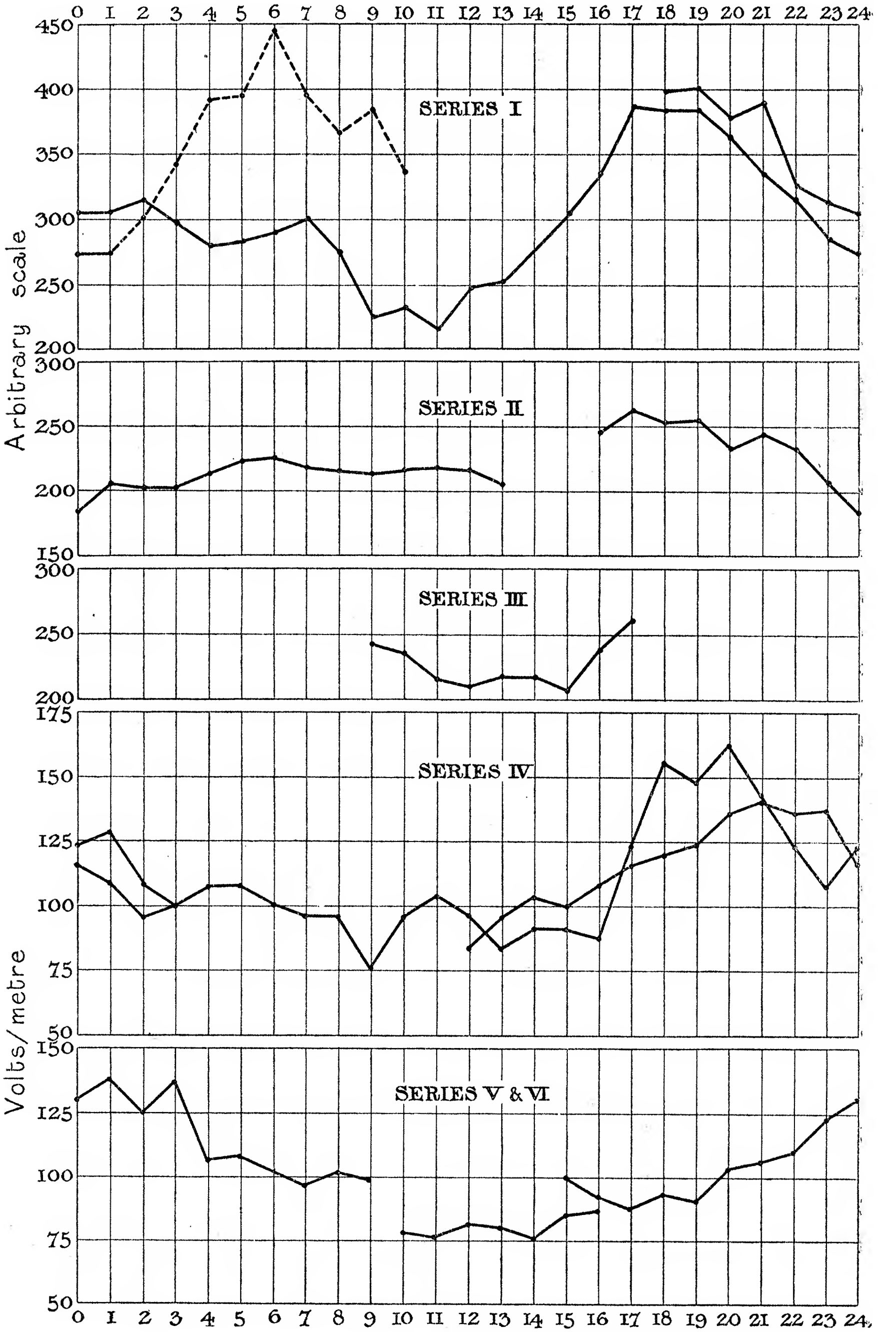

Fig. 1.

Series III was obtained on July 25, when the position of the ship was 19° 27′ S. and 29° 24′ W., within a few miles of the island of South Trinidad. The weather during this period was quite fine, with very little cloud. It is much to be regretted that this series could not have been continued, but the sails were furled soon after 17 h., and the observations had to cease.

Series IV was the most successful set of observations obtained during the whole voyage. It commenced at 11 h. 30 m. on August 3 in 30° 18′ S. and 19° 28′ W., and continued until 3 h. 30 m. on August 5 in 31° 30′ S. and 15° 0′ W. For nearly 26 h. from the commencement the sky was practically clear of clouds, but from 13 h. on the 4th the weather was very unsettled, heavy squalls passing near the ship. At 16 h. a little rain fell; the clouds then cleared somewhat until 18 h. 30 m., after which they became thick again, and between 21 h. and 23 h. there was more slight rain. From this time until the observations were stopped at 3 h. 30 m. on the 5th the weather was unsettled, and the wind rose rapidly.

After leaving Cape Town it was not expected that there would be any opportunities of making further observations of the potential-gradient, as the weather generally met with between the Cape and Australia is very rough. The weather experienced by the "Terra Nova" was, however, exceptional, and we had several days when the sea was almost smooth. On these days there was a great deal of cloud and a continual succession of small squalls, each bringing a little rain. Several attempts were made to get observations of the potential-gradient, but they were not very successful. Series V and VI were the two best.

Series V was obtained between 14 h. 30 m. on September 24 and 9 h. 30 m. on the 25th, the position of the ship being 39° 21′ S. and 84° 58′ E. at the commencement and 39° 49′ S. and 87° 19′ E. at the end. Until 23 h. on the 24th the sky was nearly clear, but from then on the weather was unsettled, and before midnight several light showers were experienced. After midnight the sky underwent very rapid changes of cloud amount, sometimes being quite overcast and a few minutes afterwards nearly clear. Finally it started to rain, and the observations had to be abandoned at 9 h. 30 m.

Series VI was obtained on September 26, the position of the ship being 40° 26′ S. and 91° 24′ E. During the observations the sky was almost cloudless, but soon after 16 h. a heavy squall came up. The weather did not clear again sufficiently to allow of the observations being continued.

The most uniform feature of the curves in fig. 1 is the rise in the potential-gradient during the afternoon and early evening. Every curve shows this, but the time at which the maximum occurs is somewhat different in each case, varying from 17 h. in Curve 1 to 1 h. in Curve 6. The latter curve, however, was no doubt largely influenced by the bad weather, and the time of maximum delayed by the showers which occurred before midnight. It appears, however, to be quite safe to conclude that the curves have their chief maximum during the evening or the early hours of the night. From this maximum each curve falls away, and there is a general tendency to fall until mid-day. All the curves reach their minimum through greater or less irregularities, which are no doubt caused by transient weather changes.*

Although these few curves leave much to be desired, they appear to show that the potential-gradient over the ocean within 40° of the Equator has its chief maximum in the evening and its chief minimum soon after mid-day.

In order to estimate the importance of these conclusions a few words must be added on the potential-gradient over the land. In high latitudes (*e.g.*, Cape Thordsen in Spitzbergen and Karasjok in Lapland) the potential-gradient has a simple daily range with a well-marked minimum at about 4 h. in the morning and a maximum between 18 h. and 21 h. in the evening. In temperate regions (*e.g.*, Kew, Paris, and Potsdam) the curve is similar, but with a second minimum superposed at about 14 h. This afternoon minimum is everywhere more pronounced in the summer than in the winter. In the tropics (*e.g.*, Batavia) the second minimum increases to such an extent that it becomes predominant, and at Batavia the 4 h. minimum is almost insignificant in comparison with the deep one at 13 h. It is generally held that the simple curve as exhibited in the winter and in high latitudes represents the fundamental march of the potential-gradient, and that the afternoon minimum is the result of the disturbance caused by the large amounts of dust which are raised by ascending currents where solar energy is intense; hence the predominance of this minimum in the summer and at low latitudes. This explanation is also supported by the fact that the potential-gradient on high mountains (*e.g.*, Sonnblick and Dodabetta) and at the top of the Eiffel Tower, which are supposed to be above the main mass of dust raised from the ground, has the simple daily curve.

It was therefore to be expected that over the ocean the simple daily range with its single minimum at 4 h. and its maximum in the early evening would be found. The curves in fig. 1 show, however, that this is not the case, for there is hardly any evidence of a minimum at 4 h. and a most marked one at about mid-day. From these results it would appear that the second minimum is not entirely due to raised dust, but is the result of some more fundamental cause.

---

* The large rise in the potential gradient shown after 1 A.M. at the end of Curve 1 was accompanied by the sudden formation at sunrise of fairly heavy clouds in a nearly clear sky; these cleared away within an hour of their formation; this part of the curve has therefore been dotted in fig. 1.

It is possible that the daily range of the potential-gradient is dependent on latitude. Our observations on the sea were all obtained within about 40° of the Equator, and they show in common with land observations within the same latitudes a predominant minimum at about mid-day; in high latitudes land observations show the predominant minimum at 4 h., while between these two extremes we have the two minima occurring together, but with varying relative intensities. May not therefore the afternoon minimum be of equal importance with the morning one, instead of being a disturbance caused by dust-charged convection currents? If this is found to be the case, then the 4 h. minimum may be considered the polar minimum and the mid-day one the equatorial minimum.

Non-periodic Changes.—With regard to minor fluctuations of the potential-gradient it may be remarked that just as is the case over the land the potential over the sea undergoes changes from minute to minute. As an example, the following readings taken at minute intervals from 14 h. to 14 h. 15 m. on August 3, have been extracted haphazard from our note-book; at the time the sky was cloudless except for a few small cumulus clouds on the horizon:—32, 30, 40, 47, 43, 57, 50, 32, 30, 31, 35, 47, 30, 55, 36, 35.

The effect of rain was found to be the same on the sea as on the land. As the rain approached the potential-gradient generally decreased, and during one period of steady rain, negative potential-gradient was noted. When, however, the rain was associated with a squall the potential-gradient took on large values, which changed rapidly from one sign to the other just as it does during a thunderstorm on land.

Absolute Value of the Potential-Gradient.—On our arrival at Melbourne (Australia) we found it possible to obtain the reduction factor for converting the relative observations of three of our series into absolute units. Within 1000 yards of the ship at anchor was a level beach, over which the equi-potential surfaces were practically horizontal. Here one of us set up the apparatus for making the absolute determinations. Two rods, with insulators on their ends, were erected 18 metres apart. In one set of readings the rods were 46 cm. high, and in another set 79 cm. Thus the field midway between them was not disturbed, for they were too far apart. A fine wire was stretched from insulator to insulator as tightly as possible, so that it was practically horizontal. To the middle of the wire an ionium collector was attached. This brought the wire to the potential in its neighbourhood, and as the wire was horizontal it lay in an equipotential surface, and so had no tendency to disturb the field. This method appears to be better than any other yet used for determining the absolute potential-gradient, since the field in the neighbourhood of the collector is as undisturbed as it is possible to obtain it.

While observations were being taken on shore, measurements were made on the ship with the conditions of yards and ropes as similar as possible to those during three of our sets of observations at sea. From the simultaneous observations the reduction factors were found, and have been applied to the figures in Columns 4, 5, and 6 of Table I. From these columns we see that the mean hourly potential-gradient on August 3 and 4 varied from 76 volt/metre to 164 volt/metre; on September 24 it varied from 87 to 138 volt/metre, while on September 24, for a few hours about mid-day, it varied around 80 volt/metre. These numbers cannot claim to have any great degree of accuracy, but, taking into account all the circumstances, it is probable that the errors are less than 25 per cent. Thus we obtain the important result that the potential-gradient over the South Atlantic Ocean and the South Indian Ocean, far away from land, is very similar in amount to that over the land.

(2) *Radioactivity.*

When Elster and Geitel discovered the presence of radioactive emanation in the atmosphere, they suggested that it owed its origin to the radium of the soil and rocks. As radium is constantly giving off emanation the interstices of the soil must be full of emanation, and Elster and Geitel experimentally demonstrated its presence. This emanation diffuses out of the earth, adding a short-lived gas to the atmosphere. Owing to the minute quantities of radium in sea-water, it seemed probable that the air over the ocean would be poor in radium emanation, especially at some distance from the coast, to which place air from the land could not reach before its emanation content had largely decreased by natural decay. That this was so appeared probable from the observations of Elster and Geitel,[*] Simpson,[†] Linke,[‡] and Dike,[§] all of whom found air from the sea to contain much less emanation than air from the land. On the other hand observations made at Palma de Mallorca[||] and Swinemunde[¶] did not give the same result; while

---

[*] 'Phys. Zeit.,' 1903, vol. 4, p. 522.

[†] 'Phil. Trans.,' 1905, A, vol. 205, p. 61.

[‡] 'Götting. Nachr.,' 1906, p. 490.

[§] 'Terr. Mag.,' vol. 13, p. 119.

[||] Elster, Geitel, and F. Harms, 'Terr. Mag.,' 1906, vol. 11, p. 1.

[¶] G. Ludeling, 'Veröff. des kgl. Preuss. Meteor. Inst.,' 1905.

Eve* made measurement over the North Atlantic Ocean, which indicated as much emanation over the centre of the ocean as he had observed in England and at Montreal. It was in the hope of reconciling these discordant results that special pains were taken to get a large amount of data during the voyage of the "Terra Nova."

The only feasible method of measuring the amount of radium emanation in the air over the sea is the one due to Elster and Geitel of exposing a negatively charged wire for two hours, and then testing it in an electroscope for induced activity. On the "Terra Nova" the wire, 810 cm. long and 0·4 mm. diameter, was stretched from one side of the ship to the other above the bridge, and this was connected by a second wire to a Braun electroscope in the small cabin which served as our physical laboratory. In order to keep the wire charged to the required negative potential (between 2000 and 2500 volts) a small influence machine was used. This was an exact copy of the "replenisher" fitted to the old form of Kelvin quadrant electrometer, but of two and a half times the linear dimensions. The "replenisher" was driven by a small spring motor which required winding every 15 minutes. Practically no difficulty was experienced in maintaining the potential even in bad weather. The insulators used throughout were of sulphur.

After the wire had been exposed for two hours it was coiled on a small aluminium frame fitting within a cylinder, 12 cm. in diameter and 10 cm. high, fixed on the top of a Wulf electroscope. The electrode of the electroscope was a small brass rod, 0·5 cm. in diameter and 9 cm. long, fitting centrally within the cylinder. The rod was charged, and then the frame holding the wire was placed around it and the cylinder closed. Five minutes after the wire had been discharged at the end of its two hours' exposure a reading of the electroscope was taken, and then further readings at intervals of five minutes. By extrapolation from these readings the loss in the first five minutes was obtained, and this was taken to be a measure of the induced activity, and so of the amount of emanation in the air.

Practically all previous observations of atmospheric radioactivity have been expressed in the arbitrary units first used by Elster and Geitel.† After exposing a wire for two hours at a potential between −2000 and −2500 volts, these physicists wound it round a cage which fitted within the instrument used by them for measuring the electrical dissipation (*Zerstreuung*). Then the activity of the air was written as 1, when 1 metre of the wire caused the potential of the electrode (*Zerstreuungskörper*) to fall 1 volt in one hour. Assuming that the active wire in our electroscope

---

[*] 'Terr. Mag.,' March, 1909.

[†] 'Phys. Zeit.,' 1902, vol. 3, p. 305.

produces as great an ionisation as it would in Elster and Geitel's instrument, the same unit may be used, if we take into consideration the difference in capacity of the two instruments. The capacity of Elster and Geitel's instrument was about 15 cm., and of ours 3·9 cm.; we have calculated our results by finding the initial fall of potential caused by 1 metre of wire in one hour, and multiplying the result by 3·9/15. The values so obtained can then be directly compared with other measurements. The letter A is generally used to denote the radioactivity of the air when expressed in Elster and Geitel's units.

On the voyage from England to Melbourne 102 observations, each extending over two hours, were taken on 55 days. The mean value of A was found to be 6, the maximum value 21, and the minimum value 1. The following table gives the results of corresponding observations made on land; in each case the observations extended over 12 months:—

Observer.	Place.	A mean.	A max.	A min.
Elster and Geitel[*] ...	Wolfenbüttel (Germany)	19	64	4
A. Gockel[†]	Freiburg (Switzerland) ...	84	170	10
G. C. Simpson[‡]	Karasjok (Lapland).........	93	432	20

[*] 'Phys. Zeit.,' 1903, vol. 4, p. 526.
[†] 'Phys. Zeit.,' 1904, vol. 5, p. 591.
[‡] 'Phil. Trans.,' A, 1905, vol. 205, p. 61.

From these results it seems certain that there is less emanation over the sea than over the land; but the two following observations remove any possible doubt.

On our arrival at Cape Town one of us took the instruments, exactly as they had been used on the ship, to Matjesfontain, 200 miles from the sea and 2970 feet above sea-level; 17 observations were made on six separate days. The mean value of A was found to be 124, A max. 256 and A min. 52. These values are much higher than anything observed at sea.

On leaving Melbourne for Lyttelton (New Zealand) an observation was made quite near to the land with an off-shore breeze, the value of A was 130. During the next few days the wind was from the south-west and the radioactivity fell to low values, the mean of four observations being A = 3. On nearing the west coast of New Zealand the wind fell light and came off the land, and A rose to 19 and then to 175.

A most interesting result is shown when the observations are tabulated according to latitude. As the number of observations on any one day varied from 1 to 12, it was thought best for this purpose to take the mean value observed on any one day, so that a single day with several observations should not outweigh other days on which only a single observation was obtained. On the journey from England to the Cape the "Terra Nova" changed her latitude rapidly, so that only a few observations could be obtained within each 10° of latitude, and consequently too much stress must not be put upon the numbers in the following table; there can, however, be no doubt that they indicate a real phenomenon:—

Latitude.	A mean.	A max.	A min.	Number of observations.
Atlantic Ocean, 40°—30° N.	7	10	4	3 obs. on 3 days.
,, 30°—20° ,,	9	12	8	14 ,, 2 ,,
,, 20°—10° ,,	13	20	7	8 ,, 3 ,,
,, 10°—0° ,,	5	8	4	6 ,, 4 ,,
,, 0°—10° S.	6	8	5	9 ,, 4 ,,
,, 10°—20° ,,	12	19	5	6 ,, 4 ,,
,, 20°—30° ,,	8	11	5	7 ,, 4 ,,
,, 30°—40° ,,	6	21	3	11 ,, 7 ,,
Indian Ocean, 40° S.	3	8	1	38 ,, 24 ,,

It will be noticed that over the Atlantic in both hemispheres the emanation increases from latitude 40° towards the Equator, but in the equatorial region itself, *i.e.* within 10° of the Equator, the emanation has a low value. The explanation of this interesting observation may probably be as follows:—

Between 30° and 40° in both hemispheres a belt of high pressure is situated in which air descends to feed the trade winds blowing towards the low pressure near the Equator. The air descending from above must be almost free from emanation owing to the short life of the latter; this no doubt accounts for the low values of A measured between 30° and 40°. As the air travels towards the Equator over the sea, it takes up emanation from the sea-water, so that the emanation content will increase in amount as the air gets further away from the place where it descended. As soon, however, as the air reaches the Doldrums it becomes thoroughly washed by the frequent heavy showers of rain, and in consequence the emanation decreases in amount. When the "Terra Nova" made her journey the Doldrums were situated to the north of the Equator and we had practically no rain between 0° and 10° S, hence the low value of A in the latter region is somewhat strange; but as stated above the number of observations was too small for details to be insisted upon.

The lowest values of all were found on the journey from the Cape to Australia, and these were no doubt due to a similar cause. The latitude on which the "Terra Nova" "ran her easting down" (about 40° S.) is south of the usual position of the region of high pressure in the South Indian Ocean;

but as the barometer was nearly half an inch above the normal during the greater part of the journey and many calm days and days with easterly winds were encountered, it is reasonable to suppose that the region of high pressure was further south than usual, and that in consequence we were always surrounded with air which had recently descended.

As far as can be seen from the observations the radioactivity over the ocean is independent of the wind velocity, and hence of the amount of broken water—the mean value of A with winds less than force 4 on the Beaufort scales was found to be exactly the same as with stronger winds. Also no relationship between the emanation and the amount of cloud could be traced.

The amount of emanation in the air over the sea is much more constant than over the land. Day after day observations were made in the morning and afternoon with almost identical results. At the commencement of the cruise it was thought desirable to see if a daily range could be detected, and so observations were continued for 24 hours with the following result, which indicates no daily range.

June 30 and July 1.

Position at commencement ...... 26° 27′ N. 20° 48′ W.
„ end .... 25° 07′ „ 21° 38′ „

Mean time.	A.	Mean time.	A.
hrs. mins.		hrs. mins.	
10 30	10	3 40	9
15 00	12	6 00	10
18 45	10	8 30	11
21 00	10	11 00	8
23 00	11	13 00	9
1 30	11	15 15	11

(3) *Ionisation.*

From the work of Langevin and others it appears that the air contains ions of a different kind from those first discovered by Elster and Geitel, and by Wilson. The essential difference is that while the latter have a mobility of about 1 cm./sec. in a field of 1 volt/cm. the former have a mobility of 1/300th part of this. There is a sharp demarcation between the two kinds of ions, for under normal conditions the air does not contain ions having specific mobilities between 0·2 and 0·0003 cm./sec. The instrument originally designed by Ebert for measuring the ionisation of the air takes account only of the faster moving ions, and these are by far the most important in the phenomena of atmospheric electricity. It is with these ions only that we are concerned in this paper.

The instrument used on the "Terra Nova" was the newest form of Ebert's instrument made by Günther and Tegetmeyer. In it the tube which forms the outer electrode of the cylindrical condenser for withdrawing the ions is vertical and of 3 cm. diameter. The inner electrode is a brass rod 141 cm. long and 0·5 cm. in diameter, and fits directly on to a Wulf electrometer. The aspirator is of the usual form supplied by this firm. When working, 91·7 litres of air pass the condenser in a minute, the electrical capacity of the condenser being 17·4 cm. According to the makers it is only necessary for the instrument to run for 5½ minutes in order to get a satisfactory determination of the ionisation. Experience showed, however, that a really satisfactory observation could not be made under 33 minutes, and most of our observations extended to 44 minutes.

Our usual method was to charge the instrument with positive electricity and leave it for half an hour or so without the aspirator running in order to determine the insulation leak. The aspirator was then set in motion and when the bell attached to the revolution counter rang a reading was taken. After each 2500 turns of the fan the bell rang again, and the instrument was wound up. After the bell had rung six times (about 11 minutes after starting) a reading of the electroscope was taken. The observation was continued for another similar interval and then again for a third. If the three readings were in good agreement, the instrument was discharged and recharged with negative electricity. If, however, the readings did not agree well the observation was continued for a fourth interval. In the same way a measurement was made with a negative charge on the condenser, and afterwards the observation with positive charge was repeated. Thus each complete observation (leaving out the period of insulation test) extended over a period of between 1 h. 40 m. and 2 h. 15 m. Only those observations have been used in the following discussion in which the complete sequence as just sketched was carried out. With the Wulf electroscope good observations were possible even when the ship was rolling to a considerable extent.

Owing to unforeseen difficulties, satisfactory determinations of the ionisation were not obtained until the "Terra Nova" had crossed the Equator and reached 10° S. latitude. From then until our arrival at Melbourne observations were taken whenever the weather permitted. During the voyage 35 complete measurements were obtained and the mean results are shown in the following table, in which I_+ stands for the quantity of positive ions contained in a cubic metre of air expressed in electrostatic units, I_- the corresponding quantity of negative ions, and q the ratio I_+/I_-.

	I_+.	I_-.	q.
E.S. units per m.^{3}	0·37	0·31	1·21

Before comparing these results with others it will be as well to discuss them in more detail.

Ionisation and Latitude.—In the Atlantic Ocean there appeared to be a distinct dependence on latitude, which seems to confirm the explanation already given for the geographical distribution of the radioactivity.

Latitude.	I_+.	I_-.	q.	Number of observations.
Atlantic Ocean, 10°—20° S.	0·30	0·22	1·36	(3)
„ „ 20°—30° S.	0·36	0·30	1·18	(8)
„ „ 30°—40° S.	0·39	0·35	1·10	(4)
Indian Ocean 40° S.	0·39	0·32	1·22	(20)

From 10° to 40° S. the ionisation increased and q decreased. If the air descends between latitudes 30° and 40°, as suggested, it would be free from dust, and the ionisation could be high even though there was only little emanation in the air. As the air travelled northwards in the trade winds it would become loaded with minute salt particles obtained from the sea; in consequence, the ionisation would decrease, and the value of q increase. In the Indian Ocean we sailed the whole way within a degree or two of 40° S., so it was impossible to test for a similar variation with latitude. The above remarks have been made by way of suggestions only, the observations being far too few to be relied on with any certainty.

Ionisation and Temperature.—The observations have been tabulated according to temperature, with the following result:—

Temperature.	I_+.	I_-.	q.	Number of observations.
< 10° C.	0·36	0·30	1·22	10
10° C.—20° C.	0·40	0·34	1·18	16
> 20° C.	0·34	0·27	1·23	9

Experiments on land have shown a marked increase of ionisation with increase of temperature; the experiments on the sea indicate the same with the exception of higher temperatures. As the latter were only met with in the trade winds (10° to 27° S.) the burdening of the air with salt may well have counterbalanced the effect of temperature.

Ionisation and Wind.—The higher the wind the more the air is filled with spray, blown off from the tops of the waves. Two effects might be expected from such breaking of the water: (1) One might expect from the Lenard effect an increase in the number of positive ions, as the splashing of salt water is known to be accompanied by the generation of positive ions; (2) the large amount of spray and salt might decrease the total ionisation, just as fog and dust have been proved to do. A division of the data according to wind strength indicates the latter effect, for, as the following table shows, both the ionisation and the ratio q are less with high winds than with light winds:—

Beaufort numbers.	I_+.	I_-.	q.	Number of observations.
0, 1, 2, and 3	0·40	0·33	1·23	16
4, 5, 6, and 7	0·35	0·30	1·18	18

The value of the ionisation measured on this voyage agrees fairly well with the only two other sets of observations made over the ocean. Eve, in a journey from Canada to England,* found $I_+ = 0·33$, $I_- = 0·26$ and $q = 1·24$. Boltzmann† found over the Atlantic Ocean $I_+ = 0·39$, $I_- = 0·27$, $q = 1·53$.

The ionisation over the land is so dependent on meteorological conditions that it is difficult to choose data to compare with our results. Perhaps the most suitable are those of one of us observed in Karasjok, in Lapland. At that place the ionisation was found to depend very largely on temperature and the results of observations at temperatures comparable with those encountered on the "Terra Nova" are shown in the following table:—‡

Karasjok (Lapland).

Temperature °C.	I_+.	I_-.	q.
5—10	0·45	0·40	1·12
10—15	0·45	0·43	1·05

These numbers are higher than those obtained over the ocean, and there can be little doubt from them and other observations made on land that the ionisation over the sea is less than that over the land under similar meteorological conditions.

---

* 'Phil. Mag.,' 1907, vol. 13, p. 248.

† 'Phys. Zeit.,' 1905, vol. 6, p. 132.

‡ Simpson, 'Phil. Trans.,' 1905, A, vol. 205, p. 61.

(4) *Ionisation of the Air in Closed Vessels as Measured over the Surface of the Ocean.*

This work was undertaken with a two-fold object in view:—(1) To determine the factors governing the variations of the ionisation in closed vessels, and particularly to investigate a possible variation due to greater or smaller quantities of radium products in the atmosphere; (2) to throw further light on the origin of this "natural ionisation," and, if possible, to determine its absolute value.

The conditions obtaining on the "Terra Nova" were particularly favourable to such work: (1) Because the sea not only contributes an inappreciable effect to the observed ionisation, but also screens off the uncertain effect of the radiations from the earth's solid crust, which is the predominating factor in measurements made on land; (2) on account of the ship's age, which might reasonably be expected to imply a greater freedom from radioactive substances than is the case with less old ships.*

Apparatus and Method of Measurement.—The ionisation vessel used in all the experiments was a zinc cylinder having a volume of 26,500 c.c. Previous work has shown that zinc vessels are not subject to the increase of ionisation in the course of time, which takes place with cylinders of lead and possibly other metals,† and zinc has also the advantage of giving a low absolute value for the natural ionisation.

The cylinder was cleaned in April, 1910, by sandpapering and washing with hydrochloric acid, ammonia, alcohol, and distilled water, and dry dust-free air immediately introduced. After this the cylinder was closed, but not hermetically sealed.

A glance at the accompanying diagram (fig. 2) will show the method of measurement. The cylinder A‡ was insulated by the ebonite pegs B, and the ebonite collar C, and kept at a high and constant potential by a battery of small dry cells sufficient to give a saturating voltage. These cells,§ 50 in number, were embedded in paraffin wax, and weighed about 20 lbs., and throughout the whole series of observations acted in a most satisfactory manner. The electrode E was screwed into the rod carrying the quartz fibres of a Wulf electroscope.

---

[*] Wright, 'Phil. Mag.,' February, 1909, p. 310.

[†] McLennan, 'Phil. Mag.,' December, 1907.

[‡] In the figure the cylinder A is shown much smaller relative to the electroscope than it was in reality.

[§] Furnished by the Ecco Battery Co., Bow Common Lane, London, E.

In making a measurement, the cylinder A and the insulated inner case G of the electroscope are connected to the positive terminal of the dry cells. By pushing in the key D, and then withdrawing it, the electrode is earthed, and the quartz fibres deflected. In the course of time this deflection decreases, and the rate of decrease (about 10 volts per hour) gives a measure of the ionisation current. As the rate of decrease during the second hour was always appreciably the same as during the first, no correction has been applied for defective insulation.

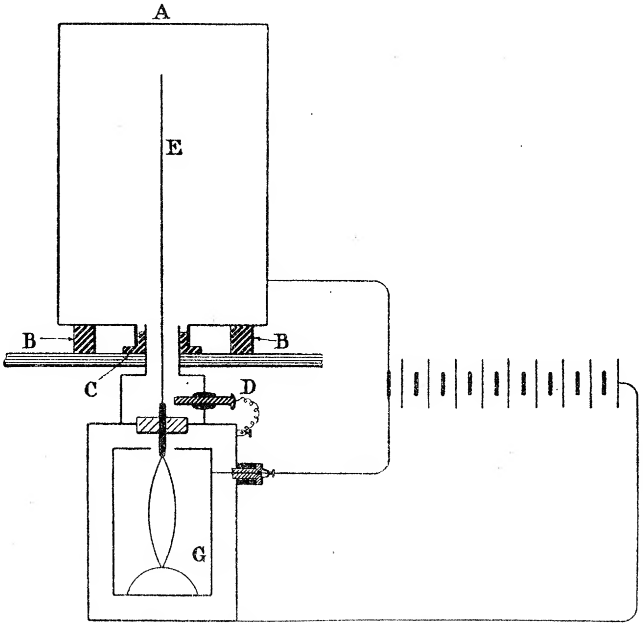

Fig. 2.

The capacity of the electrode system is found by applying a known potential to the inner case G, and noting the potential to which the electrode system is raised. A repetition of this proceeding with a known capacity then readily gives all the data required for determining the capacity of the whole system. The error of any single observation (duration one hour) may be put down as 3·5 per cent., depending on the amount of the ship's motion. A typical set of readings for a complete 24 hours is given in Table II.

In Tables III, IV, and V are shown the analyses of the results from Madeira to Melbourne (Australia); the former series being marked "A" and the latter "B." The suffix numbers represent the number of observations used in calculating the mean value. The total number of hourly observations was about 250.

Table II.

September 24, 1910. Mean time.	Ions per c.c. per sec.	September 25, 1910. Mean time.	Ions per c.c. per sec.
h. m.		h. m.	
9 30	6·3	0 30	6·5
10 30	6·2	2 30	7·0
11 00	6·4	4 30	6·9
12 30	6·4	5 30	6·8
17 30	6·6	7 30	6·9
19 30	6·8	9 00	6·2
21 00	6·7	11 00	6·3
22 00	6·8	12 30	6·4
23 00	6·6		

Capacity of system = 9·4 cm.

Table III.

Time of day......	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
q (A)..................	6·5 (1)	6·4 (1)	6·3 (2)	—	6·4 (2)	6·1 (1)	5·9 (1)	6·6 (3)	6·5 (11)	6·3 (18)	6·4 (19)	6·4 (8)
q (B)..................	—	6·5 (1)	—	7·0 (1)	6·9 (1)	6·8 (1)	6·9 (1)	—	6·3 (11)	6·2 (22)	6·2 (16)	6·3 (19)

Time of day......	13.	14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.
q (A)..................	6·5 (13)	6·7 (11)	6·4 (12)	6·5 (10)	6·5 (9)	6·4 (7)	6·4 (5)	6·4 (1)	6·4 (2)	6·0 (2)	6·3 (2)	6·0 (1)
q (B)..................	6·3 (17)	6·1 (18)	6·2 (13)	6·3 (9)	6·4 (3)	6·9 (1)	6·6 (2)	6·9 (1)	6·6 (2)	6·8 (1)	6·6 (2)	6·5 (1)

Table IV.

A = rad^{y}. of air ...	0–5.	5–10.	10–15.	15–20.	20–25.	25–30.	30–35.	35–40.	40–45.	45–∞.
q (A)	—	6·4 (2)	6·7 (5)	6·2 (2)	6·4 (7)	6·7 (2)	—	—	6·0 (1)	6·4 (3)
q (B)	6·1 (4)	6·3 (11)	6·2 (5)	5·7 (1)	6·2 (1)	—	—	6·5 (1)		

Table V.

	q (A).	q (B).
Barometer over 30·2 inch	6·36 (8)	6·15 (13)
,, under 30·2 inch	6·70 (12)	6·40 (12)

It may be noted (Tables III and IV) that evidence of a regular daily variation or of any connection between the observed ionisation and the radium-content of the air is quite lacking. No certain connection, moreover, was found with air temperature, sea temperature, rainfall, or quantity of coal in the adjacent bunkers.

Though in individual cases no relation between ionisation and pressure could be traced, still a fairly definite and well-marked connection was shown when the mean of all observations was taken (Table V), a high barometer corresponding to a low value of q.

Though in general the observed variations were within a few per cent. of the mean value, still on several occasions, when the ship was close to land, appreciably higher numbers were obtained. Thus, when anchored off South Trinidad Island, the value of q rose from 6 to 8, dying away to the former value a few hours after leaving the island. Unfortunately, no observations on the radium-content of the air were taken while anchored off the island.

Again, at Melbourne, the ionisation rose from 6·5 to 9, falling again to 6·8 about twenty hours after reaching the open sea. Simultaneously with the occurrence of this high value was recorded a value for the radioactivity of the air, $A = 130$, but the high ionisation persisted for some time after the air radioactivity fell again to $A = 3$.

On another occasion, when nearing New Zealand (the cylinder having been recleaned in the meantime), the value of q changed from 4 to 5, and returned to 4 thirty-six hours afterwards. Concurrent with this high value, the radium-content of the air was represented by $A = 175$, though again the high ionisation persisted for some twenty-four hours after A had fallen to its normal value.

Possibly the most interesting feature of the series of observations is the lack of any regular daily variation in the natural ionisation over the ocean; for though Gockel,* Wright,† and Cline‡ have been unable to detect any variation whatever over the land, many observers, including Wood and Campbell,[*] Strong,[†] and Wulf[‡] have found fairly large variations.

---

* Gockel, 'Phys. Zeit.,' 1908, vol. 9, p. 907.

† Wright, 'Phil. Mag.,' February, 1909.

‡ Cline, 'Bull. Roy. Soc. Canada,' October, 1909.

As a result of their investigations, Campbell and Wood have found a double daily period in the natural ionisation, whose maxima and minima correspond with the maxima and minima of the earth's potential gradient. The generally accepted explanation for this correspondence is that the radioactive products in the atmosphere have a greater tendency during high positive gradients to be deposited on the earth's surface than during low or negative potential-gradients, and may thus reinforce the penetrating radiation from the earth.

A simple calculation shows what effect might be expected from an annihilation of the RaC in the atmosphere.

Taking

Q = Ra equivalent in air[§] = 10^{-16} grm. per c.c.,
K = number of ions generated per c.c. per sec. in a zinc vessel by 1 grm. Ra at 1 cm. distance,[||]
q = number of ions in the vessel due to RaC in air,
λ = coefficient of absorption of air = 0·00004, and
r = distance from the cylinder,

we have

$$q = 2\pi K Q \int_0^\infty \frac{r^2 \,.\, e^{-\lambda r}}{r^2}\, dr,$$

$$= 2\pi \frac{KQ}{\lambda} = 0{\cdot}05.$$

It is therefore clear that variations in the penetrating radiation from the RaC in the atmosphere cannot be the cause of the observed variations.

Of more importance, possibly, will be the deposition of RaC on the ground, corresponding to a decrease in the radium-content of the air. Let us assume that all the RaC in a layer of air 1 kilometre thick is suddenly deposited on the earth's surface, supposed flat, and, in order to simplify calculations, let us assume that λ-air = zero.

Ra equivalent on earth's surface = 10^{-11} grm. per sq. cm.

Then $$q = \int_{100}^{100{,}000} KQ \frac{2\pi r \,.\, dr}{r^2} = 2\pi KQ \Big[\log_e r\Big]_{100}^{100{,}000},$$

$$= 1{\cdot}9,$$

---

[*] Campbell and Wood, 'Phil. Mag.,' 1907, [6], p. 2.

[†] Strong, 'Phys. Zeit.,' 1908, vol. 9, p. 117.

[‡] Wulf, 'Phys. Zeit.,' 1909, vol. 10.

[§] Eve, 'Terr. Mag.,' March, 1909; Satterly, 'Phil. Mag.,' July, 1910.

[||] Eve, *loc. cit.*

taking the electroscope as 1 m. from the ground and assuming that only that surface within a kilometre will affect the air in the cylinder.

There is thus a possibility that the RaC carried down in this way may produce a measurable effect on the ionisation. Probably a more efficacious agent than the earth's potential gradient, in depositing radioactive products on the ground, would be the occurrence of heavy rain storms, and the consequent carrying down of the products by the falling rain. Though observations connecting natural ionisation with rainfall are few in number, still Mache and Rimmer,* and Gockel,† have found that the ionisation increases sometimes as much as 100 per cent. after a heavy thunder shower.

Though effects of this magnitude may be possible over or near the land, it may well be expected that such causes will have little or no effect on the natural ionisation over the sea, chiefly because the radium-content of sea air is distinctly smaller than that of land air, but also because any radioactive product deposited upon the sea surface will go into solution and be quickly disseminated.

That the variations noted by certain observers on land are really due to variations in the amount of radioactive products present on the ground in the vicinity of the observing station can now no longer be doubted, though it may well be that in certain places these variations are too small to be measurable.

Thus it was seen that near land a high radioactive-content of the air almost synchronised with a high natural ionisation. That this high ionisation is due to radioactive products deposited on the ship itself is highly probable from the fact that the ionisation persisted for some time after the high air radioactivity had disappeared. It may also be deduced from the slow rate of decrease that thorium products, in at least some cases, played a considerable part.

Absolute Value of the Natural Ionisation.—Many efforts have been made during late years to reduce the number of ions generated in metal vessels to their lowest possible number, both by careful cleaning of the vessel to free it from radioactive deposits on the walls, and by screening from the earth's penetrating radiation.

The lowest value of q yet obtained (and as yet unpublished) for an unscreened vessel over the land is 8 ions. This number was found in a zinc cylinder of length 60 cm. and diameter 24 cm., the vessel being under observation in the new wing of the Cavendish Laboratory at Cambridge. The cylinder, after the most careful cleaning, was filled with dry dust-free air, which had been slowly passed through a worm immersed in liquid air, and also through a brass tube with a coaxial wire charged to a high potential, in order to make sure that no radium emanations or products were admitted with the air.

---

* Mache u. Rimmer, 'Phys. Zeit.,' 1906, vol. 7, p. 617.

† Gockel, 'Phys. Zeit.,' November, 1909.

Still lower values of q have been obtained by screening the vessel from the earth's penetrating rays. Among those who have attempted such "screening" experiments may be mentioned Cook,* McLennan and Burton,† Wright,‡ and Gockel.§ These experiments show that water furnishes the best natural screen against the penetrating rays from the earth. Thus, over the ice of Toronto Bay (Lake Ontario) the very low value of $q = 4{\cdot}4$ ions (recalculated for $e = 4{\cdot}6 \times 10^{-10}$) was obtained in a zinc cylinder of approximately 27 litres capacity, this number being a decrease of 5·5 ions from the value obtained in the laboratory.

In the present series of observations it was therefore thought advisable to compare the measurements made over the sea with similar observations on land, and with observations in a small skiff, in order to eliminate the possible effect of radioactive impurities in the hull of the "Terra Nova." The results are given in Table VI, and show a difference between land and sea values of about 6 ions.

Table VI.

Position.	q.	Difference between land and sea.	Remarks.
"Terra Nova," Simon's Bay ...	6·3	—	In laboratory.
Matjesfontein	12·3	6·0	1·5 m. from ground (in open).
"Terra Nova," Lyttelton	6·3	—	At dock.
Small skiff	4·1	2·2	In open bay, 100 m. from breakwater.

Now since the mean quantity of Ra in the sea-water is $Q = 1{\cdot}6 \times 10^{-14}$,‖ a simple calculation shows that the number of ions in the cylinder due to this agency is $q = 0{\cdot}005$.

We may therefore safely say that over the sea the number of ions in the cylinder due to penetrating rays from terrestrial sources (air, land, and water) is not more than 0·1. Thus the number in Column 3, Table VI, represents within 0·1 ion that part of q due to the radioactive substance in or on the soil at the position of observation.

Moreover, by the observations in the small skiff, we have obtained the low value of 4·1 ions per cubic centimetre per second in this zinc cylinder a number almost exactly the same as that obtained a few days previously on the "Terra Nova" in the open sea, after the cylinder had been cleaned again, and when the ship was presumably free from radioactive deposits.

---

* Cook, 'Phil. Mag.,' 1909, [6], vol. 7, p. 140.

† McLennan and Burton, 'Phil. Mag.,' 1903, [6], vol. 5, p. 707.

‡ Wright, *loc. cit.*

§ Gockel, 'Phys. Zeit.,' November, 1909.

‖ Joly, Presidential Address, Brit. Assoc., Dublin, 1908.

It will be seen that in this case, as with all previous attempts to reduce the value of q by screening the ionisation vessel from the earth's penetrating radiation, there remains a residual ionisation due to causes other than penetrating rays from terrestrial sources.

Three possible contributors to this residual ionisation need alone be considered here:—

(1) Emanation within the vessel and admitted with the gas.
(2) Intrinsic radioactivity of the metal or radioactive impurities in it.
(3) Spontaneous ionisation or breakdown of the enclosed gas.

(1) *Radioactive Emanation in the Gas.*—A calculation from known data of the number of ions due to and particles shot out from Ra Em. and other radium products present in the cylinder and admitted with the air shows, on the assumption that all α-particles are totally absorbed in the gas, and that the amount of Ra Em. in the air is 10^{-16} grm. per cubic centimetre,* that in the mean 1·3 ions alone may be put down as due to emanation in the air of the vessel. Experiments, however, have shown that admitting the air slowly through a spiral immersed in liquid air has caused no diminution in the observed value of q, and it would seem possible that the filtering of the air through cotton wool extracted all the emanation.

(2) *Radioactivity of Metal or Radioactive Impurity in it.*—The belief in the possibility of an intrinsic activity of all metals, and in the possibility of radioactive impurities, has been considerably strengthened since the discovery of the radioactivity of potassium and rubidium, and the separation of a radioactive substance (RaF) from samples of commercial lead. In this connection it might be well to point out that lead is the metal with which the rise in conductivity in the course of time is most marked, and that those metals, as zinc, which show no rise may reasonably be supposed free from impurities. It would therefore seem probable that our zinc vessel was at least free from radioactive impurity.

(3) *Spontaneous Ionisation of the Gas.*—The possibility that the residual natural ionisation may be due to a spontaneous breakdown of the gas is one which has of late received but scant attention. Calculations have, indeed, been made† to show that the mechanical shock in the collisions of gas molecules, by virtue of their kinetic motion, is quite insufficient to account for the production of the required 4 ions per cubic centimetre per second.

---

* Eve, 'Terr. Mag.,' March, 1909.

† Karl Bergwitz, F. Vieweg u. Sohn, Braunschweig, 1910.

This calculation, however, is on the assumption that the kinetic energy of motion is directly convertible into the electrical energy within the atom.

Since, however, it is known that the metal rubidium* is capable even in the dark of emitting electrons from itself, it appears by no means certain that gaseous molecules have not the same property to a greater or less extent. On this view we might well expect that a heavy gas with many electrons would be more easily ionised than a light one. Jaffé† has, indeed, shown that for nickel carbonyl the natural ionisation is about five times that of air, and for hexane‡ an even larger number (12·6) is recorded.

In further support of the theory of a spontaneous ionisation in gases is the fact that each observer has found the same values for q in vessels of all metals except those of lead, which alone is known to contain a radioactive impurity.

We see also that on this view the relation between air pressure and residual ionisation will be a linear one,§ the value of q depending only on the number of molecules within the vessel. The small changes in ionisation due to changes of barometric pressure, however, would usually be masked by other factors called into play by these changes.

It is probable that a careful series of observations on the relation between pressure and q in a perfectly screened cylinder might well prove the truth or falsity of the theory of a spontaneous ionisation of the gas, and in any case can hardly fail to give valuable information regarding the origin of the residual ionisation in closed vessels.

The results of the observations on natural ionisation may be stated as follows:—

(1) No regular daily variation has been found over the sea.

(2) A slight dependence of the natural ionisation upon barometric pressure has been observed—a high barometer giving a low value of q.

(3) The number of ions in a zinc cylinder due to penetrating radiation from the soil at Matjesfontein has been found to be 6.

(4) It has been found that a considerable addition ($q = 3$) to the normal ionisation, as measured on the ship, may be contributed by radioactive products deposited on the ship, and due primarily to a high value for the radium-content of the air.

(5) The lowest number of ions per cubic centimetre per second observed in a closed zinc cylinder of 27 litres capacity over the sea is 4.

---

[*] Sir J. J. Thomson, 'Conduction through Gases,' p. 251.

[†] Jaffé, 'Phil. Mag.,' October, 1904, p. 556.

[‡] Jaffé, 'Ann. d. Phys.,' February 4, 1909, vol. 28, (2), p. 326.

[§] Burton, 'Phys. Rev.,' 1904, vol. 18, p. 3.